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Lumbar spine stability can be augmented with an abdominal belt and/or increased intra-abdominal pressure

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Abstract The increased intra-abdominal pressure (IAP) commonly observed when the spine is loaded during physical activities is hypothsized to increase lumbar spine stability.The mechanical stability of the lumbar spine is an important consideration in low back injury prevention and rehabilitation strategies. This study examined the effects of raised IAP and an abdominal belt on lumbar spine stability. Two hypotheses were tested: (1) An increase in IAP leads to increased lumbar spine stability, (2) Wearing an abdominal belt increases spine stability. Ten volunteers were placed in a semi-seated position in a jig that restricted hip motion leaving the upper torso free to move in any direction. The determination of lumbar spine stability was accomplished by measuring the instantaneous trunk stiffness in response to a sudden load release. The quick release method was applied in isometric trunk flexion, extension, and lateral bending. Activity of 12 major trunk muscles was monitored with electromyography and the IAP was measured with an intra-gastric pressure transducer. A two-factor repeated measures design was used ($P < 0.05$), in which the spine stability was evaluated under combinations of the following two factors: belt or no belt and three levels of IAP (0, 40, and 80% of maximum). The belt and raised IAP increased trunk stiffness in all directions, but the results in extension lacked statistical significance. In flexion, trunk stiffness increased by 21% and 42% due to 40% and 80% IAP levels respectively; in lateral bending, trunk stiffness increased by 16% and 30%. The belt added between 9% and 57% to the trunk stiffness depending on the IAP level and the direction of exertion. In all three directions, the EMG activity of all 12 trunk muscles increased significantly due to the elevated IAP. The belt had no effect on the activity of any of the muscles with the exception of the thoracic erector spinae in extension and the lumbar erector spinae in flexion, whose activities decreased. The results indicate that both wearing an abdominal belt and raised IAP can each independently, or in combination, increase lumbar spine stability. However, the benefits of the belt must be interpreted with caution in the context of the decreased activation of a few trunk extensor muscles.

Key words Lumbar spine, stability · Lumbar spine, intra-abdominal pressure · Lumbar spine, abdominal belts · Lumbar spine, electromyography

Introduction

Chronic low back pain (LBP) creates a profound socioeconomic problem in today's society [17, 18, 28, 51, 70]. Recent studies support the hypothesis that patients suffering from LBP of mechanical origin try to compensate for their injuries with additional or different muscle recruitment patterns, presumably to increase spine stability [4, 9, 14, 56, 61]. In healthy individuals, mechanical stability is provided to the spine by trunk muscles and ligaments [5, 6, 11, 19, 20]. Injuries and chronic mechanical defects in the osteoligamentous structures reduce spine stability [53]. To maintain a normal level of stability, trunk muscles must compensate by altering their normal activation pattern [54, 55]. The question of whether wearing the abdominal belt or the rise in the intra-abdominal pressure (IAP) can increase the lumbar spine stability to protect it from acute low back injury, still remains unanswered.

The early hypotheses that the IAP relieves part of the compressive loads borne by the lumbar spine [1, 27, 49] have been accepted by some [12, 22, 34, 35, 65, 66] and refuted by others [2, 29–31, 42, 50, 52]. The current consensus seems to be that the compressive forces, arising from the contraction of abdominal wall musculature to generate the IAP, offset the beneficial action of the hydrostatic forces thought to alleviate spinal compression via IAP. The increased IAP commonly observed when the spine is loaded during physical activities is hypothesized to increase lumbar spine stability [41–44, 63]. For example, patients with nonspecific low back pain exhibit higher IAP during lifting than normal controls [16, 23]. The IAP also increases in response to a sudden trunk loading in healthy individuals [10]. The above cited studies indirectly point towards the association of IAP with the mechanical stability of the lumbar spine. However, direct experiments are needed to test this hypothesis.

Abdominal belts have been shown to help individuals in generating higher IAP levels during load-handling activities [22, 34, 35, 43]. There exists anecdotal evidence that people "feel safer" wearing abdominal belts when exerting large forces [38]. This is especially true for weight lifters and power lifters, who use belts apparently for no obvious benefit other than to increase their IAP during lifting [22, 34, 35]. While a few studies reported marginal improvement in lifting capacity with the use of abdominal belts [59, 62], the overwhelming evidence suggests that belts have no effect on muscle strength [37, 39, 58], fatigue [8, 39], or low back injury incidence [48, 57, 69]. Although one of the epidemiological studies claimed that belt wearing reduced the number of low back injuries [32], several methodological flaws make such interpretation of the results questionable. The most serious concern was that the belt wearing policy was not the sole ergonomic intervention implemented at the time of this study. At the present time, it appears that abdominal belts are widely prescribed in industry and rehabilitation without a convincing scientific justification of their benefits [3, 13, 24, 45, 47, 68]. Often reported subjective feelings of increased support may stem from abdominal belts passively increasing trunk stiffness and/or reducing its range of motion [21, 36, 46, 60, 64]. However, the direct evidence that belts modulate spine stability is still lacking.

The purpose of the present study was to examine the effect of IAP and wearing an abdominal belt on lumbar spine stability by measuring trunk stiffness with a quick release method in trunk flexion, extension, and lateral bending. Two hypotheses were tested:

1. An increase in IAP leads to increased lumbar spine stability, and
2. Wearing an abdominal belt helps to increase spine stability. Activity of major trunk muscles was monitored with electromyography to add to the interpretation of results.

Materials and methods

This was a two-factor experimental design in which spine stability, a dependent variable, was evaluated under a combination of two independent variables: wearing or not wearing the abdominal belt and the level of intra-abdominal pressure (IAP). The determination of lumbar spine stability was accomplished by measuring the instantaneous trunk stiffness in response to a sudden load release that subjects were resisting (quick release method). Electromyographic signals (EMG) from major trunk muscles were recorded before and after the release to add to the interpretation of results.

Ten subjects with no previous history of low back pain (average age 28, SD 4 years; height 177, SD 7 cm; weight 78, SD 14 kg) were placed in a semi-seated position in a jig that restricted hip motion leaving the upper torso free to move in any direction (Fig. 1). In the quick release method, the subjects exerted isometric trunk extension, flexion, and lateral bending to the left, at 35% of their maximum, resisting a cable attached to a chest harness at approximately the T9 level. The cable was held with an electromagnet, which was suddenly released by the researcher (without warning the subject) when the required force level was achieved. The resulting trunk motion was measured at 100 Hz with an inductive sensor (Flock of Birds, Ascension Technologies, VT) placed on the back at the T9 level.

The EMG signals were recorded from 12 muscles (left and right rectus abdominis, external and internal oblique, latissimus dorsi, thoracic and lumbar erector spinae) according to a previously established protocol [5, 6]. The signals were band-pass preamplified between 20 and 500 Hz, amplified, and converted to digital data at 1600 Hz. It was assumed that a muscle activation pattern established prior to a sudden trunk perturbation determines the spine stability and, in turn, the kinematics of the trunk response to that perturbation. Accordingly, 200 ms of EMG data, recorded immediately before the magnet release, were digitally rectified and averaged. The baseline EMG values, recorded when the subjects were lying completely relaxed, were subtracted from the quick release EMG. These baseline signals contained mostly electrode and amplifier noise. Finally, the data were normalized to the EMG activity recorded during the maximum voluntary contractions (MVC). With the exception of lateral bending trials, left and right EMG values were averaged.

The IAP was measured with a transducer (Micro-tip MPC500, Millar Instruments, TX) inserted into the stomach via the nasoesophageal pathway. The subjects were instructed to increase their IAP with the Valsalva maneuver and to hold it at the indicated

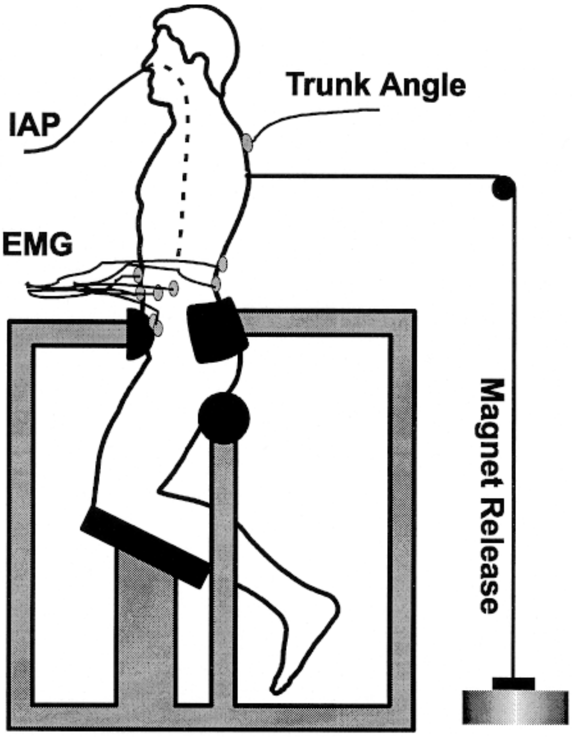

Fig. 1 A subject positioned in a hip motion restraining apparatus. The intra-abdominal pressure (IAP) was built up with Valsalva maneuver up to the target level, while subjects resisted the cable load of 35% of their maximum. Stability was assessed upon the electromagnet release of the cable load

level while slowly increasing the trunk isometric force. The IAP and the desired IAP target level lines were displayed on an oscilloscope for visual feedback to the subjects. Once the trunk isometric force had reached its target, without warning, the researcher initiated the data collection by releasing the electromagnet. All data were collected in the about trigger mode for 1 s before and 2 s after the release.

Values for trunk stiffness were obtained from the trunk motion data in accordance with a standard quick release protocol [25, 26, 33, 67, 72]. The trunk was modeled as a second-order system with viscoelastic properties oscillating freely after the release of a moment that subjects were resisting. Amplitude and frequency of such oscillations measured immediately after the release, but before voluntary muscle intervention took place, were determined by trunk inertia (I), damping coefficient (B) and stiffness coefficient (K) established prior to the release:

$$I\ddot{\theta} + B\dot{\theta} + K\theta = mgL\sin\theta \tag{1}$$

where θ is the trunk angle, *mg* is trunk weight, and L is the height measured from the L5-S1 joint to the center of trunk mass, assumed to be at T9 level. Trunk mass and moment of inertia were calculated from the subject's weight and height [71]. Coefficients *B*, *K* and one additional integration constant *C* were obtained with a curve fitting algorithm where the objective was to gain the best match between the modeled and measured trunk rotation trajectories. This procedure was applied to the double integrated Equation 1 [67], because integration is numerically a more robust operation than differentiation:

$$I\theta + B\int\theta\,dt + K\iint\theta\,dt^2 + Ct^2 = mgL\iint\sin\theta\,dt^2 \tag{2}$$

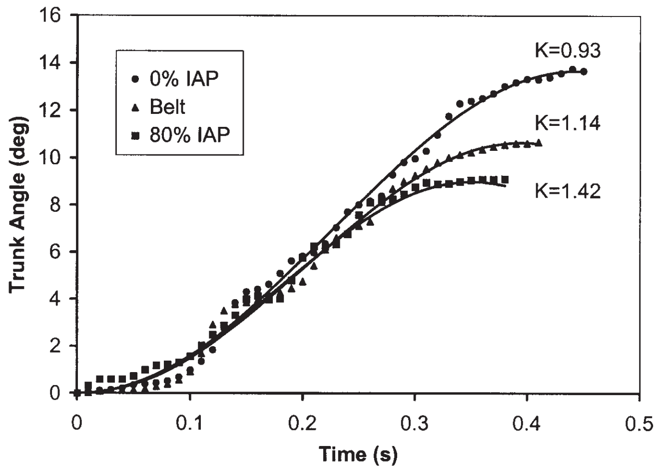

Fig. 2 An example of the trunk rotation responses to sudden unloading. The three curves represent trials under the following conditions: (0% IAP) a subject was instructed not to increase his intra-abdominal pressure, (80% IAP) a subject was instructed to reach a target set at 80% IAP, (Belt) a subject was wearing an abdominal belt and was instructed not to increase his intra-abdominal pressure. Markers indicate the raw data and the lines indicate a curve fit according to the Equation 2. *K* = Normalized trunk stiffness

A preliminary study indicated that the minimum length of a data record needed to identify parameters in the Equation 2 accurately was equivalent to at least one-quarter of the wavelength. Therefore, angular trunk motion data, taken from the time of magnet release to the point of maximum trunk deflection, was used for a curve fit (Fig. 2).

In each quick release direction, three trials were performed at each of the three IAP levels (0, 40, and 80% of individual's maximum). To reduce the testing time, only the 0% and 80% IAP trials were repeated while wearing a standard 10-cm-wide nylon belt (model SANB4, Altus Athletic, Altus, OK). A force of 180 N, measured with a spring scale, was used to tighten the belt while the subjects were actively attempting to minimize their waist circumference. This force was used to standardize the belt tightness to a moderate, comfortable level. All trials were performed in a randomized order.

Trunk stiffness coefficients were averaged between three trials and normalized for each subject to the stiffness value obtained with no belt and no IAP. The effect of belt and IAP level, (independent variables), on trunk stiffness, (a dependent variable), was tested with two-factor, repeated measures ANOVA (2 × 3 unbalanced design, $P < 0.05$).

Results

On average, Equation 2 fitted the trunk angular deflection data with Root mean square (RMS) error of 0.47° (SD = 0.56°) (Fig. 2). Although the subjects were instructed to maintain their IAP level at a given target, some variation was present. In addition, it was not possible to have no IAP when generating isometric trunk exertions. Therefore, the average (SD) IAP values measured at the time of magnet release were 14.1 (5.8), 42.8 (8.0), and 71.3 (9.3) % of maximum for the trials labeled as 0, 40, and 80% respectively.

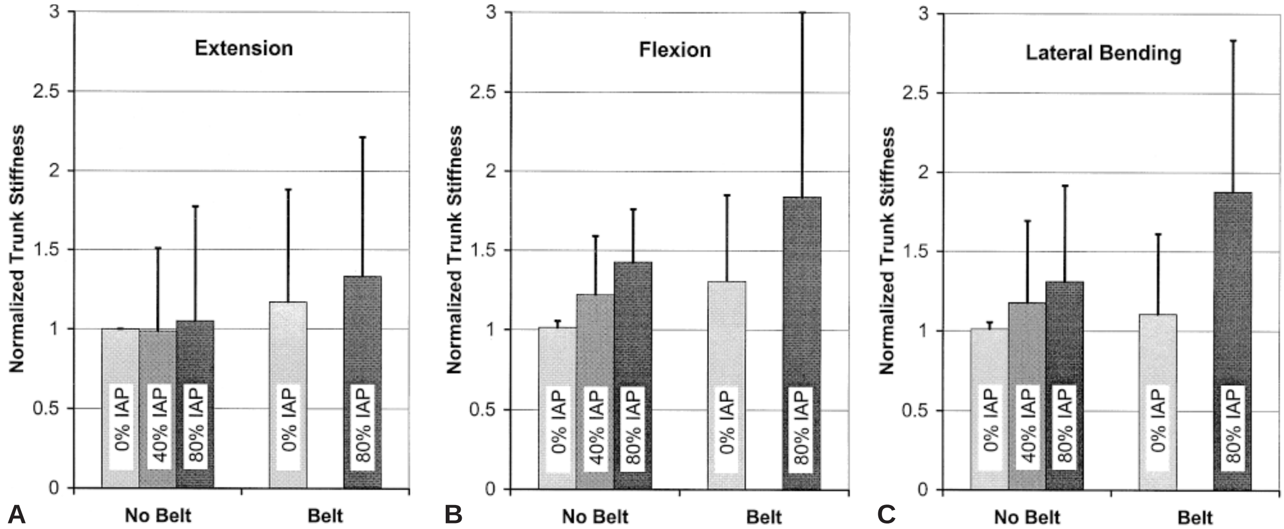

Fig. 3 A–C Normalized trunk stiffness obtained from a quick release method for various combinations of intra-abdominal pressure and belt conditions. **A** Quick release in trunk extension, **B** flexion, and **C** lateral bending to the left

Both the belt and IAP increased trunk stiffness in all directions, but the results in extension lacked statistical significance and will not be emphasized further (Fig. 3 A). There were no interactions between the belt and IAP effects in any of the three directions. In flexion, trunk stiffness increased by 21% and 42% due to 40% and 80% IAP levels respectively (Fig. 3 B); in lateral bending, trunk stiffness increased by 16% and 30% (Fig. 3 C). With no IAP, the belt increased trunk stiffness by 29% and 9% in flexion and lateral bending respectively. At 80% of maximum IAP, the belt added 41% to the trunk stiffness in flexion and 57% in lateral bending. The effects of both factors on trunk stiffness were additive. Thus, the combined effects of wearing an abdominal belt and the increased IAP level to 80% of maximum provided 83% and 86% more trunk stiffness in flexion and lateral bending respectively.

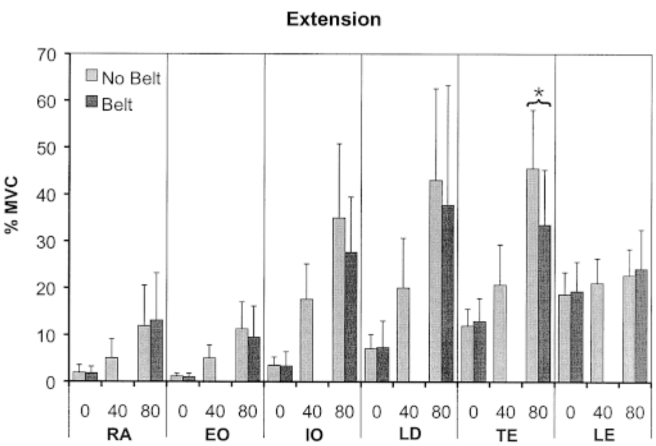

Fig. 4 Intra-abdominal pressure (% maximum) and belt effects on muscle activity (% maximum voluntary contraction, MVC) averaged 200 ms prior to the load release in trunk extension trials (*RA* rectus abdominis, *EO* external oblique, *IO* internal oblique, *LD* latissimus dorsi, *TE* thoracic erector spinae, *LE* lumbar erector spinae)

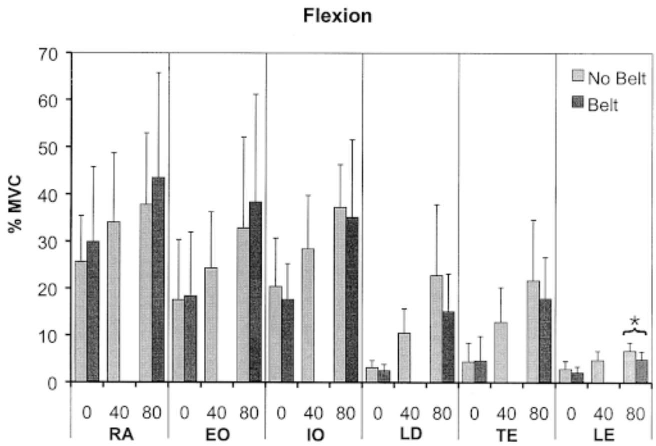

Fig. 5 Intra-abdominal pressure (% maximum) and belt effects on muscle activity (% MVC) averaged 200 ms prior to the load release in trunk flexion trials

In all three directions, the EMG activity of all 12 trunk muscles increased significantly due to the increased IAP (Figs. 4–6). The belt had no effect on the activity of any of the muscles, with the exception of the thoracic erector spinae in extension and the lumbar erector spinae in flexion. Activity of those muscles decreased significantly only at 80% IAP level due to wearing the belt (Figs. 4, 5).

Discussion

Effects of the increased intra-abdominal pressure (IAP) and the wearing of an abdominal belt on lumbar spine sta-

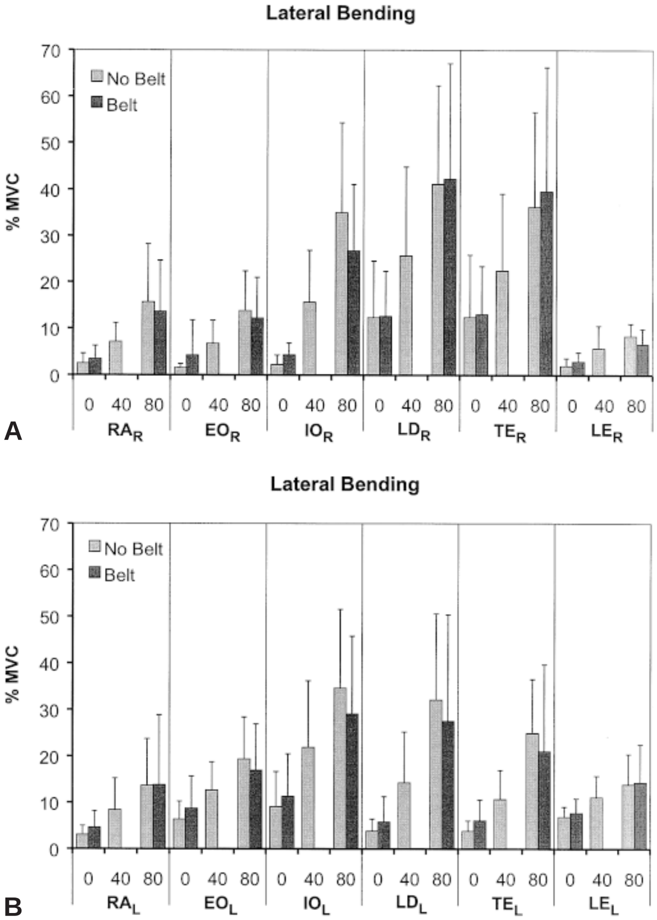

Fig. 6 A, B Intra-abdominal pressure (% maximum) and belt effects on muscle activity (% MVC) averaged 200 ms prior to the load release in trunk lateral bending to the left trials. **A** Right side muscles, **B** left side muscles (Subscripts *R* and *L* indicate the side)

bility were studied by measuring the kinematics of trunk response to a sudden load release, according to the so-called quick release protocol. The more stable the structure prior to a perturbation (load release in this case), the smaller is its deflection amplitude and the higher is its oscillation frequency in response to that perturbation (Fig. 2). To quantify these trunk displacements, Equation 2 was used. Although Equation 2 represents a simplified model, it fit the experimental data very well (average RMS error < 0.5°).

In a quick release method, the stability of a multi degree-of-freedom system is characterized by the aggregate mechanical impedance parameters: inertia, damping, and stiffness coefficients. The latter (stiffness) determines the stability of the static equilibrium. It was this stiffness that was used in the present study to quantify spine stability at the time of load release. All three coefficients computed from the trunk kinematics were dependent on the formulation of the model and the assumed height, mass, and inertia parameters (Equation 2). However, because the same model was used in all conditions tested for each individual, and because only relative values of stiffness were analyzed, the reliability of the results was assured.

The results indicated that both wearing an abdominal belt and increased IAP can each independently, or in combination, increase trunk stiffness, and therefore, increase lumbar spine stability under sudden loading/unloading conditions. However, the activation patterns of trunk muscles suggest that the mechanisms of the spine stabilization are different for those two factors. It is likely that the increase in spine stability due to IAP was gained from the concomitant increase in muscle coactivation needed to generate a high IAP. This observation is consistent with the IAP mechanism described by Cholewicki et al. [7]. These authors demonstrated with a physical and biomechanical model that the contraction of abdominal muscles necessary to create IAP would stiffen the lumbar spine area.

Stabilizing the lumbar spine with the belt alone is most likely a passive mechanism stemming from the interaction of the wide and stiff belt placed between the ribcage and pelvis. In contrast to the increased IAP effect, there was virtually no change in muscle activity whether the belt was worn or not. The exception of the thoracic and lumbar erector spine muscles, whose activation was significantly smaller when the belt was worn in trunk extension and flexion respectively, indicates further that a passive, and not an active, mechanism was responsible for the increased spine stability. These results are consistent with McGill et al. [46], who reported an increase in passive trunk stiffness in lateral bending and axial rotation due to wearing an abdominal belt.

While it is clear that a belt itself contributes to lumbar spine stability, as does the voluntary increase in IAP, its benefits must be interpreted with caution. The fact that the activity of some muscles decreased when the belt was worn may indicate the reduction in overall muscle coactivation causing reduction in active spine stabilization by the muscles. Perhaps subjects perceived added stiffness derived from the belt, and they therefore decreased muscle coactivation. If this is the case, long-term abdominal belt usage may lead to regression of the active spine stabilizing system. This hypothesis would be consistent with the outcome of a large study dealing with the incidence of low back injury and long-term belt usage among airline workers [57]. They found that abdominal belt use did not reduce overall incidence of back injuries. However, when the belts were removed after several months, frequency of low back injuries increased. If our subjects had had time to get used to wearing the belt, we might not have seen any increase in the spine stability. The belt effect might have been negated completely by decreased muscle coactivation. Future studies should address the effects of long-term belt usage on spine stability and on the stabilizing function of trunk musculature.

Although the effects of IAP and a belt on spine stability were studied here only in an upright posture, the results could be extrapolated to other tasks and kinds of lumbar supports. If the increase in IAP is possible in a given posture, then the increase in spine stability will follow by the virtue of abdominal muscle coactivation. If the belt passively stiffens the trunk in an upright posture, it is likely that this effect will be even more pronounced when the spine moves away from the neutral posture, or when a wider and stiffer belt is used. However, the spine is most vulnerable to loss of stability when it is in a neutral posture [5, 6]. While only the trunk-unloading mode was studied, it was used to estimate the instantaneous trunk stiffness and consequently the stability of the lumbar spine in the state in which it was at the time of load release. If the spine becomes more stable, it will exhibit greater resistance to perturbation, irrespective of whether this perturbation occurs in a spine loading or unloading mode. Furthermore, the quick release tasks, used in this study to estimate spine stability, may simulate spine unloading events occurring during sudden slips and trips that often result in an accidental low back injury while handling loads [40].

The findings of the present study are relevant to the design of low back injury prevention and rehabilitation strategies. Increased spine stability may provide greater protection against injury following unexpected or sudden loading. Therefore, the increased IAP and/or muscle coactivation observed in low back pain patients and prescription of abdominal belts may serve to compensate the initial injury to the spine and to restore or increase its stability [54, 55]. Lumbar supports and orthotics are among the commonly prescribed modalities for prevention and treatment of low back pain. There exists a concern, however, that a long-term usage of lumbar supports may lead to trunk muscle weakness [15] and increased risk of injury when the wearing of lumbar supports is discontinued [57]. In some specific cases, abdominal belts may be beneficial in helping injured workers return earlier to work [69]. Improved understanding of the mechanism by which IAP and abdominal belts increase lumbar spine stability will help to define better both the target population and the length of time for the treatment with lumbar supports to be the most effective.

The variability among the individual trunk stiffness values along with variability in muscle activation patterns suggests some interaction among active spine stabilizing strategies. Cholewicki et al. [7] identified two possible mechanisms by which trunk muscles can stabilize the lumbar spine. One was antagonistic muscle coactivation and the second was activation of only the abdominal musculature and generation of IAP. Using a physical model, they demonstrated that both of these mechanisms might function separately or in combination, leading to different critical load (stability) values. To verify this hypothesis, calculations of spine stability should be performed with a detailed mathematical model [5] using the EMG values obtained in this study as input. If the muscle activation patterns alone can predict the spine stability, then the IAP and abdominal belt mechanisms for stabilizing the lumbar spine hypothesized here and by Cholewicki et al. [7] will be supported. Future studies may also provide an explanation for the lack of a more pronounced increase in spine stability due to the IAP and belt in trunk extension.

Conclusions

1. Both wearing an abdominal belt and raising IAP can each independently, or in combination, increase lumbar spine stability.
2. Increase in spine stability due to high IAP is likely gained from the concomitant increase in muscle coactivation needed to generate this IAP. In contrast, the stabilizing effect of the belt alone appears to be a passive mechanism.

References

1. Bartelink DL (1957) The role of abdominal pressure in relieving the pressure on the lumbar intervertebra discs. J Bone Joint Surg Br 39:718–725
2. Bearn JG (1961) The significance of the activity of the abdominal muscles in weight lifting. Acta Anat 45:83–89
3. Bridger RS (1998) Abdominal belts for manual handling in industry: the evidence for and against. South African J Physiother 54:12–15
4. Cassisi JE, Robinson ME, O'Conner P, MacMillan M (1993) Trunk strength and lumbar paraspinal muscle activity during isometric exercise in chronic low-back pain patients and controls. Spine 18:245–251
5. Cholewicki J, McGill SM (1996) Mechanical stability of the in vivo lumbar spine: Implications for injury and chronic low back pain. Clin Biomech 11:1–15
6. Cholewicki J, Panjabi MM, Khachatryan A (1997) Stabilizing function of trunk flexor/extensor muscles around a neutral spine posture. Spine 22:2207–2212
7. Cholewicki J, Juluru K, McGill SM (1999) Intra-abdominal pressure mechanism for stabilizing the lumbar spine. J Biomech 32:13–17
8. Ciriello VM, Snook SH (1995) The effect of back belts on lumbar muscle fatigue. Spine 20:1271–1278
9. Cooper RG (1993) Understanding paraspinal muscle dysfunction in low back pain: a way forward? Ann Rheum Dis 52:413–415
10. Cresswell AG, Oddsson L, Thorstensson A (1994) The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. Exp Brain Res 98:336–341
11. Crisco JJ, Panjabi MM (1990) Postural biomechanical stability and gross muscular architecture in the spine. In: Winters JM, Woo SL-Y (eds) Multiple muscle systems: biomechanics and movement organization. Springer, New York, pp 438–450

12. Daggfeldt K, Thorstensson A (1997) The role of intra-abdominal pressure in spinal unloading. J Biomech 30: 1149–1155
13. Dillingham TR (1998) Lumbar supports for prevention of low back pain in the workplace. J Am Med Assoc 279:1826–1828
14. Dolce JJ, Raczynski JM (1985) Neuromuscular activity and electromyography in painful backs: psychological and biomechanical models in assessment and treatment. Psychol Bull 97: 502–520
15. Eisinger DB, Kumar R, Woodrow R (1996) Effect of lumbar orthotics on trunk muscle strength. Am J Phys Med Rehabil 75:194–197
16. Fairbank JC, O'Brien JP, Davis PR (1980) Intraabdominal pressure rise during weight lifting as an objective measure of low-back pain. Spine 5: 179–184
17. Frymoyer JW (1990) Magnitude of the problem In: Weinstein JN, Weisel SW (eds) The lumbar spine. WB Saunders, Philadelphia, pp 859–869
18. Frymoyer JW, Cats-Baril W (1991) An overview of the incidences and costs of low back pain. Orthop Clin North Am 22:263–271
19. Gardner-Morse M, Stokes IAF, Laible JP (1995) Role of muscles in lumbar spine stability in maximum extension efforts. J Orthop Res 13:802–808
20. Gardner-Morse MG, Stokes IA (1998) The effects of abdominal muscle coactivation on lumbar spine stability. Spine 23:86–91
21. Granata KP, Marras WS, Davis KG (1997) Biomechanical assessment of lifting dynamics, muscle activity and spinal loads while using three different styles of lifting belt. Clin Biomech 12:107–115
22. Harman EA, Rosenstein RM, Frykman PN, Nigro GA (1989) Effects of a belt on intra-abdominal pressure during weight lifting. Med Sci Sports Exerc 21:186–190
23. Hemborg B, Moritz U (1985) Intra-abdominal pressure and trunk muscle activity during lifting – chronic low-back patients. Scand J Rehabil Med 17:5–13
24. Hodgson EA (1996) Occupational belt use: a literature review. AAOHN J 44: 438–443
25. Hogan N (1990) Mechanical impedance of single- and multi-articular systems. In: Winters JM, Woo SL-Y (eds) Multiple muscle systems: biomechanics and movement organization. Springer, New York, pp 149–164
26. Hunter IW, Kearney RE (1982) Dynamics of human ankle stiffness: variation with mean ankle torque. J Biomech 15:747–752
27. Keith A (1923) Mans posture: its evolution and disorders. Lecture IV. The adaptations of the abdomen and its viscera to the orthograde posture. BMJ 1:587–590
28. Kelsey JL, White AA (1980) Epidemiology and impact of low back pain. Spine 5:133–142
29. Krag MH, Gilbertson LG, Pope MH (1984) A test of the hypothesis of abdominal pressure as a disc load-reducing mechanism: a study using quantitative electromyography. Proc Am Soc Biomech, Tucson
30. Krag MH, Gilbertson LG, Pope MH (1985) Intra-abdominal and intra-thoracic pressure effects upon load bearing of the spine. Proc 31st Annual Meeting of Orthop Res Soc, January 21–24, Las Vegas, pp 328
31. Krag MH, Byrne KB, Gilbertson LG, Haugh LD (1986) Failure of intra-abdominal pressurization to reduce erector spinae loads during lifting tasks. Proc North Am Congr Biomech, August 25–27, Montreal, pp 87–88
32. Kraus JF, Brown KA, McArthur DL, Peek-Asa C, Samaniego L, Kraus C (1996) Reduction of acute low back injuries by use of back supports. Int J Occup Environ Health 2:264–273
33. Lacquaniti F, Licata F, Soechting JF (1982) The mechanical behavior of the human forearm in response to transient perturbations. Biol Cybern 44:35–46
34. Lander JE, Simonton RL, Giacobbe JKF (1990) The effectiveness of weight-belts during the squat exercise. Med Sci Sports Exerc 22:117–126
35. Lander JE, Hundley JR, Simonton RL (1992) The effectiveness of weight-belts during multiple repetitions of the squat exercise. Med Sci Sports Exerc 24:603–609
36. Lavender SA, Thomas JS, Chang D, Andersson GBJ (1995) Effect of lifting belts, foot movement, and lift asymmetry on trunk motions. Hum Factors 37: 844–853
37. Lavender SA, Chen SH, Li YC, Andersson GBJ (1998) Trunk muscle use during pulling tasks – effects of a lifting belt and footing conditions. Hum Factors 40:159–172
38. Magnusson M, Pope MH, Hansson T (1996) Does a back support have a positive biomechanical effect? Appl Ergonom 27:201–205
39. Majkowski GR (1998) The effect of back belt use on isometric lifting force and fatigue of the lumbar paraspinal muscles. Spine 23:2104–2109
40. Manning DP, Mitchell RG, Blanchfield LP (1990) Body movements and events contributing to accidental and nonaccidental back injuries. Spine 9: 734–739
41. Marras WS, Mirka GA (1996) Intra-abdominal pressure during trunk extension motions. Clin Biomech 11: 267–274
42. McGill SM, Norman RW (1987) Reassessment of the role of intra-abdominal pressure in spinal compression. Ergonomics 30:1565–1588
43. McGill SM, Norman RW, Sharratt MT (1990) The effects of an abdominal belt on trunk muscle activity and intra-abdominal pressure during squat lifts. Ergonomics 33:147–160
44. McGill SM, Sharratt MT (1990) Relationship between intra-abdominal pressure and trunk EMG. Clin Biomech 5: 59–67
45. McGill SM (1993) Abdominal belts in industry: a position paper on their assets, liabilities and use. Am Ind Hyg Assoc J 54:752–754
46. McGill SM, Seguin J, Bennett G (1994) Passive stiffness of the lumbar torso in flexion, extension, lateral bending and axial rotation. Effect of belt wearing and breath holding. Spine 19:696–704
47. Minor SD (1996) Use of back belts in occupational settings. Phys Ther 76: 403–408
48. Mitchell LV, Lawler FH, Bowen D, Mote W, Asundi P, Purswell J (1994) Effectiveness and cost-effectiveness of employer-issued back belts in areas of high risk for back injury. J Occup Med 36:90–94
49. Morris JM, Lucas DB, Bresler B (1961) The role of the trunk in stability of the spine. J Bone Joint Surg Am 43:327–351
50. Nachemson AL, Andersson GBJ, Schultz AB (1986) Valsalva manoeuvre biomechanics: effects on lumbar trunk loads of elevated intra-abdominal pressures. Spine 11:476–479
51. Nachemson A, Spitzer WO, et al. (1987) Scientific approach to the assessment and management of activity-related spinal disorders: a monograph for clinicians. Report on the Quebec Task Force on Spinal Disorders. Spine 12 [Suppl 1]:S1–S59
52. Örtengren R, Andersson GBJ, Nachemson AL (1981) Studies of relationships between lumbar disc pressure, myoelectric back muscle activity and intra-abdominal (intragastric) pressure. Spine 6:76–82
53. Oxland TR, Panjabi MM (1992) The onset and progression of spinal injury: a demonstration of neutral zone sensitivity. J Biomech 25:1165–1172
54. Panjabi MM (1992) The stabilizing system of the spine. I. Function, dysfunction, adaptation, and enhancement. J Spinal Disord 5:383–389

55. Panjabi MM (1992) The stabilizing system of the spine. II. Neutral zone and instability hypothesis. J Spinal Disord 5:390–397
56. Panjabi MM (1996) Low back pain and spinal instability. In: Weinstein JN, Gordon SL (eds) Low back pain: a scientific and clinical overview. American Academy of Orthopaedic Surgeons, Rosemont, pp 317–332
57. Reddell CR, Congleton JJ, Hutchingson RD, Montgomery JF (1992) An evaluation of a weight lifting belt and back injury prevention training class for airline baggage handlers. Appl Ergonom 23:319–329
58. Reyna JR, Leggett SH, Kenney K, Holmes B, Mooney V (1995) The effect of lumbar belts on isolated lumbar muscle strength and dynamic capacity. Spine 20: 68–73
59. Smith EB, Rasmussen AA, Lechner DE, Gossman MR, Quintana JB, Grubbs BL (1996) The effects of lumbosacral support belts and abdominal muscle strength on functional lifting ability in healthy women. Spine 21:356–366
60. Sparto PJ, Parnianpour M, Reinsel TE, Simon S (1998) The effects of lifting belt use on multijoint motion and load bearing during repetitive and asymmetric lifting. J Spinal Disord 11:57–64
61. Stokes MJ, Cooper RG, Morris G, Jayson MIV (1992) Selective changes in multifidus dimensions in patients with chronic low back pain. Eur Spine J 1:38–42
62. Sullivan MS, Mayhew TP (1995) The effect of lumbar support belts on isometric force production during a simulated lift. J Occup Rehabil 5:131–143
63. Tesh KM, Dunn JS, Evans JH (1987) The abdominal muscles and vertebral stability. Spine 12:501–508
64. Thoumie P, Drape JL, Aymard C, Bedoiseau M (1998) Effects of a lumbar support on spine posture and motion assessed by electrogoniometer and continuous recording. Clin Biomech 13:18–26
65. Troup JDG (1977) Dynamic factors in the analysis of stoop and crouch lifting methods: a methodological approach to the development of safe materials handling standards. Orthop Clin North Am 8:201–209
66. Troup JDG, Leskinen TPJ, Stålhammar HR, Kuorinka IAA (1983) A comparison of intraabdominal pressure increases, hip torque, and lumbar vertebral compression in different lifting techniques. Hum Factors 25:517–525
67. Tsuji T, Morasso PG, Goto K, Ito K (1995) Human hand impedance characteristics during maintained posture. Biol Cybern 72:475–485
68. Van Poppel MNM, Koes BW, Smid T, Bouter LM (1997) A systematic review of controlled clinical trials on the prevention of back pain in industry. Occup Environ Med 54:841–847
69. Van Poppel MNM, Koes BW, van der Ploeg T, Smid T, Bouter LM (1998) Lumbar supports and education for the prevention of low back pain in industry – a randomized controlled trial. J Am Med Assoc 279:1789–1794
70. Videman T, Battie MC (1996) A critical review of the epidemiology of idiopathic low back pain. In: Weinstein JN, Gordon SL (eds) Low back pain: a scientific and clinical overview. American Academy of Orthopaedic Surgeons, Rosemont, pp 317–332
71. Winter DA (1990) Biomechanics and motor control of human movement, 2nd edn. John Wiley, New York
72. Winters J, Stark L, Seif-Naraghi A-H (1988) An analysis of the sources of musculoskeletal system impedance. J Biomech 12:1011–1025